REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
19-01-2010	Final Report	1-Jul-2006 - 31-Oct-2009

4. TITLE AND SUBTITLE

Novel Non-Volatile Memory Devices Based on Magnetic Semiconductor Nanostructures for Terabit Integration

5a. CONTRACT NUMBER

W911NF-06-1-0267

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

611102

6. AUTHORS

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)

ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

49373-EL.1

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

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14. ABSTRACT

This research project exploited carrier spin-dependent properties in nanoscale magnetic structures for novel spin device applications. Particularly, it aimed at demonstrating the viability of non-volatile spin memory concepts that can be highly scalable, can have extremely low power dissipation, and can be merged with the silicon compatible platform. The primary focus of the effort was on the device concepts utilizing electrical control of the magnetism, which is one of the main advantages of the semiconductor-based magnetic nanostructures over the metallic

15. SUBJECT TERMS

magnetic structures, graphene, correlated phenomena, nonvolatile devices, spintronics

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Ki Wook Kim
UU	UU	UU	UU		19b. TELEPHONE NUMBER: 919-515-5229

Final Technical Report on

"Novel Non-Volatile Memory Devices Based on Magnetic Semiconductor Nanostructures for Terabit Integration"

ARO Grant No: W911NF-06-1-0267

1. Statement of the problem studied

This research project exploited new spin-dependent phenomena or concepts utilizing the unique properties of graphene for carbon based spintronics as well as more conventional semiconductor based magnetic systems. The primary focus of the effort was on the device concepts utilizing electrical control of the magnetism, which is one of the main advantages of the semiconductor-based magnetic nanostructures over the metallic counterparts. Combined with developments in the materials research, the proposed device concepts could lay the ground for low-power nonvolatile memory and programmable logic elements beyond the current technological limit.

2. Summary of the most important results

- We demonstrated theoretically the feasibility of a multiple functional device cell through electrical control of the paramagnetic-ferromagnetic (PM-FM) phase transition [1] in a semiconductor quantum dot (QD) separated from the reservoir of itinerant holes by a barrier (Fig. 1). The parameter window suitable for bistability was established along with the conditions that support maximum non-volatility. The limitation of QD size scaling was analyzed in terms of the system lifetime. In addition, the dynamic energy dissipation in the Write/Erase process was estimated and an efficient readout scheme was exploited based on the two-terminal configuration. The proposed non-volatile device is expected to have the following advantages compared to the conventional CMOS-based memory: (i) excellent scalability, potentially down to a few hole level; (ii) low energy dissipation under the high speed Write/Erase operation; (iii) high integration density (through the use of only two contacts in a pillar form); and (iv) potential application as the logic devices.

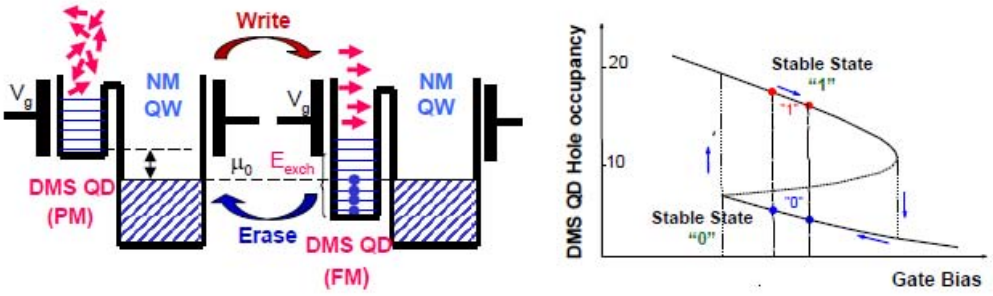

Figure 1: Left – Schematic illustration of the multifunctional switch based on the electrical control of PM-FM phase transition. Right – Hysteresis loop showing the variation of QD hole density as a function of applied bias. The upper (lower) solid curve represents FM (PM) state of the QD. At the zero bias, the system can be found either in the "0" (PM) or "1" (FM) state. Switching between these states can be achieved by gate bias pulses (blue arrows). The system remains stable either at "1" or "0" even after the bias is turned off (i.e., nonvolatile).

- We proposed and theoretically explored a non-volatile memory device based on electrical modulation of the local magnetization of a FM layer (via magnetic polaron formation [2]). The envisioned structure consists of a magnetic dielectric layer and a lateral quantum dot that share an interface (Fig. 2). The hole population in the quantum dot is controlled by the particle exchange with an adjacent reservoir of itinerant holes over a permeable barrier. A theoretical model based on the free energy analysis demonstrated the existence of bistable states through the mechanism of bound collective magnetic polaron, whose formation and dissolution can be controlled electrically via gate bias pulses. The parameter window space suitable for bistability was established along with the conditions that support maximum non-volatility. It was found that the interplay between the exchange interaction and the insulator magnetic anisotropy is the key to realizing the memory concept. The analysis was extended to the influence of material choices as well as different designs. For the structure under consideration, a practically non-volatile condition (operating at room temperature) may be achieved for the quantum dots scaled down to approx. 15-20 nm.

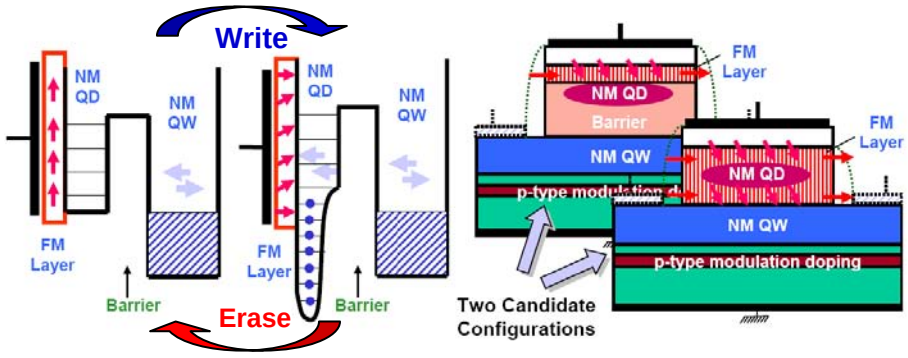

Figure 2: Left – Hybrid memory device concept based on magnetic polaron formation. The operation of this device is similar to that shown in Fig. 1. The difference stems from the use of nonmagnetic semiconductor that is in contact with a ferromagnetic dielectric layer. The subsequent exchange interaction between the holes and proximate magnetic ions provides the necessary binding force for bistability. Right – Potential implementation of the concept in a pillar form.

- A spin field effect transistor was proposed by utilizing a graphene layer as the channel (Fig. 3). Similar to the conventional spin field effect transistors [3], the device involves spin injection and spin detection by ferromagnetic source and drain. The key idea is the use of a ferromagnetic dielectric layer between the channel and the gate electrode. Due to the negligible spin-orbit coupling, the conventional approach based on the so-called Rashba effect [4] cannot be applied in the carbon-based structures. Instead, the proposed device controls the electron exchange interaction with the magnetic ions of the dielectric layer (through the gate bias), which in turn results in the modulated spin rotation in the graphene channel and the output current in the drain. This effect can be amplified significantly when a multiferroic material can be used (room temperature examples include Ba doped $BiFeO_3$), in which not only the electron overlap with the magnetic ions but also the magnetization itself in the dielectric layer can be changed by an electrical bias. A theoretical analysis demonstrated the feasibility of this concept as a low-power logic device.

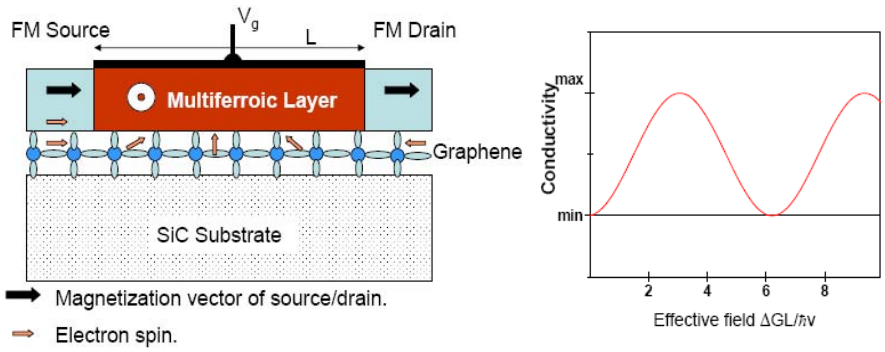

Figure 3: Left – Spin FET utilizing a graphene channel (circles with bonds) and a ferromagnetic gate dielectric. The ferromagnetic source and drain have collinear magnetic moments along the channel direction (large arrows), while the ferromagnetic dielectric directs its magnetization normal to the plane (filled circle with a dot). When an applied bias V_g alters the exchange interaction and subsequently the degree of spin rotation, the electron has a finite probability to be collected by the drain. Right – Schematic illustration of channel conductivity modulation as a function of effective field controlled by the gate bias.

- We explored new spin-dependent concepts by utilizing the unique properties of graphene. Specifically, the multilayered composite structures were exploited that take advantage of the atomically thin nature of graphene in combination with magnetic films. The idea is to introduce desired magnetic properties to the system through the proximate interactions between graphene electrons and magnetic ions of the magnetic materials at the interfaces, which in turn may be controlled electrically. The feasibility of this concept was theoretically investigated in a simple three layered structure where graphene is placed between two ferromagnetic dielectric materials (Fig. 4). The calculation based on a tight-binding model illustrated that the magnetic interactions at the interfaces [5] affect not only the graphene band structure but also the thermodynamic potential of the system, leading to an effective exchange bias between adjacent magnetic layers. More

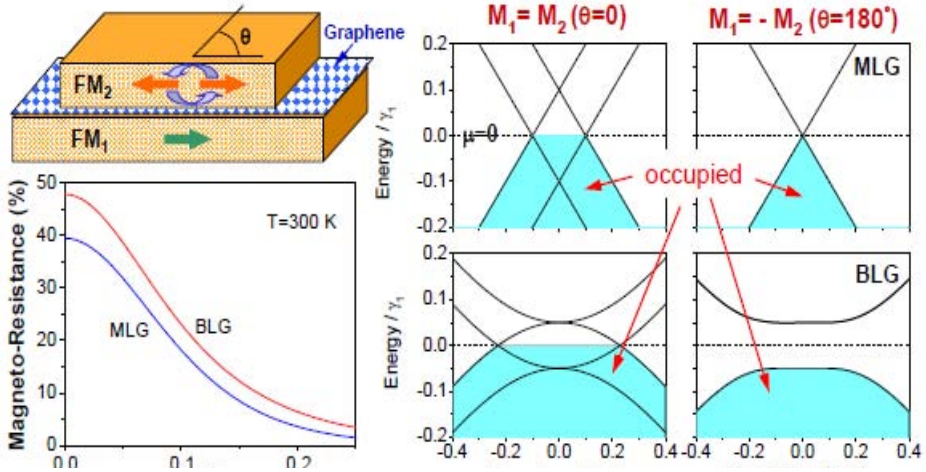

Figure 4: Top Left – Schematic illustration of graphene sandwiched between ferromagnetic dielectric layers of magnetization. The magnetization of the top layer can be rotated in reference to that of the bottom layer (with angle θ). Right – Change in energy band structure as a result of magnetization misalignment (i.e., rotation). MLG denotes monolayer graphene and BLG bilayer graphene. This also affects the free energy of the system. Bottom Left – Resulting change in the graphene conductance (i.e., the GMR effect). $\gamma_1 = 0.4$ eV.

importantly, the analysis demonstrated a strong dependence of this exchange bias [6] on the properties of mediating layer, revealing an efficient mechanism of electrical control even at room temperature. If realized experimentally, this offers a significant opportunity in the field of spintronics as electrical control of magnetism is generally very difficult to achieve.

- We proposed and theoretically analyzed a low-power non-volatile magnetic switch (Fig. 5) based on the finding discussed above. The basic mechanism relies on electrically controlled rotation of magnetic bits via modulation of graphene mediated exchange bias field between adjacent magnetic layers. Readout of magnetization states can also be achieved electrically through the magneto-resistance effect in the graphene channel described above. The proposed switch can be used to realize both memory and logic elements. Theoretical estimates illustrated the feasibility of the concept as well as its potential advantage including low power consumption (as low as 10^{-19} J for intrinsic switching operation), non-volatility, scalability, and programmability. Moreover, the device can achieve a complete set of the universal logic gates with only a slight variation in the design.

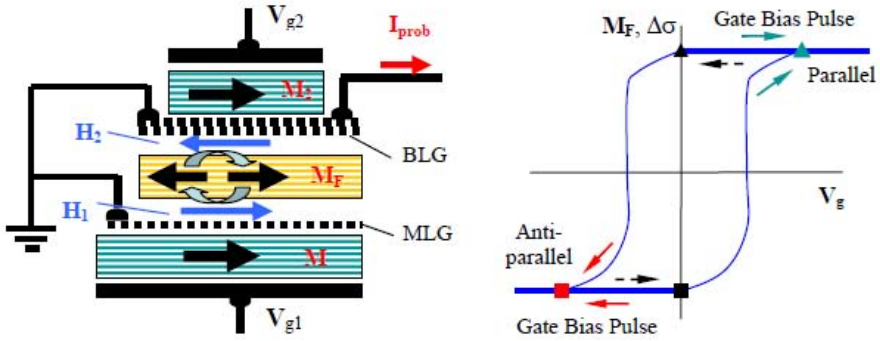

Figure 5: Left – Magnetic switch employing both mono- and bilayer graphene for nonvolatile memory and logic applications. Two antiferromagnetic layers placed between the ferromagnetic layers (FM_1 and FM_2) and the gate electrodes are not shown. Right – Predicted magnetization reversal of the middle ferromagnetic layer (M_F) and subsequent change in the graphene channel conductance ($\Delta\sigma$) as a function of gate bias V_g ($=V_{g1}= V_{g2}$).

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[6] See, for example, J. Nogue´s and I. K. Schuller, J. Magn. Magn. Mater. 192, 203 (1999); and references therein.